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Blast effects on spatial glass shells for a long-span roof structure

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Abstract

Modern railway stations are often designed architecturally to embed long-span roof structures to enhance portal bird-eye views for commuters and dwellers. Commonly, slender-by-nature spatial glass shell elements are installed over such the long-span roof structure. The span/depth ratio of the shell elements often causes excessive responses and high sensitivity to dynamic actions (e.g. wind, Earthquakes, explosion, etc.). The issues are pronounced when thin-walled glass roof structures experience shock loads. At present, terrorist attack is one of the global grand challenges for engineers to resolve. Especially in Europe, the railway stations are considered to be at extreme risk of terrorist exposure. This implies that the activity could occur imminently. Also, many railway critical infrastructures were built or designed long before the explosive actions being taken into account. In this study, the blast simulation and transient effects on a long-span glass roof structure are thus highlighted. The focus is placed on spatial glass shell elements, which are ones deemed to be at risk. Nonlinear modeling, validation and transient analyses of the station roofing structure have been carried out using a finite element package, LS-Dyna. The explosion is simulated by rapid and abrupt release of energy using LS-Dyna code. The explosion effects are highlighted in a waveform of high intensity pressure that spreads outward from the source to the surrounding air. It is designed to place the blast load close to the escalators because the location can affect most people/structure. Nonlinear transient dynamic results can be obtained. In this study, critical fragility and vulnerable component analyses will be presented so that railway and structural engineers can develop risk-based retrofit program against terrorist attacks for the railway station. Sensitivity of explosion intensity has been evaluated to quantify structural capacity and vulnerability of the glass shell roof. The insight into this transient behavior will help railway and structural engineers to establish strategic retrofitting methods to minimise catastrophic damage to and potential losses of train passengers, the public & rail assets.

Keywords: blast, transient effect, response, long span, spatial shell, glass shell roofing, railway station

1. Introduction

Over the past 30 years, terrorist attacks in Western Europe have remained a constant threat (very likely to happen) [1]. The number of historical attacks and fatalities can be seen in Figure 1. Therefore, it is of paramount importance to consider blast attack resistance in all design processes of new built environments and the assessment of existing ones in order to mitigate risks and minimise hazards to the public. To put the physical and cyber threats into context, areas of high importance and potential targets include train stations, airports, shopping centres, sport stadiums, malls, concert halls and theatres. In other words, anywhere that could have a large number of casualties or have a detrimental effect on transport and infrastructure networks or the economy [2].

Design against blast loading is an ongoing and vital research subject in structural engineering [1-3]. This is a direct result of the constant threat of terrorism around the globe; infrastructure posing a significant risk appears to be associated with the public transportation system where the potential for mass disruption and destruction is greatest [4]. A study [5] stated that 89 terrorist attacks were targeted at the transportation system sector between 1970 and 2015 in America. These statistics are able to bolster the research into blast resistant design in critical infrastructure. Modern technologies have allowed architecture to produce elegant, slender structures that optimise the use of space in very compact environments such as cities. These constraints lend themselves to the utilisation of thin shells, which derive their strength from their shape and are known as form resistant structures [6]. The application of thin shells maximise the efficiency of construction materials through membrane theory where out of plane forces are able to be resisted by in plane responses. The compromise between blast resistance and structural slenderness is ongoing topic to design a blast resistant glass.

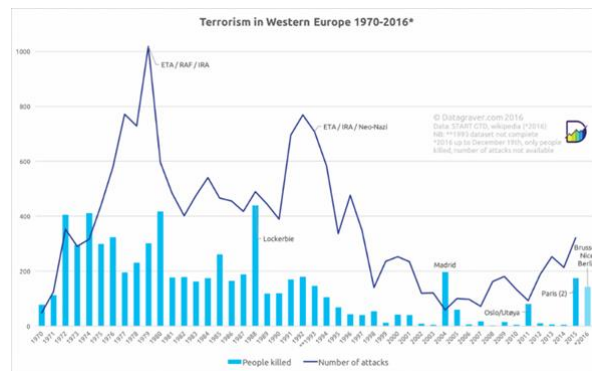


Figure 1: Terrorism statistics in Western Europe

This paper investigates the dynamic responses of curved glasses subjected to blast pressures. The expulsion of glass panes has previously been considered beneficial in order to relieve internal pressures; however the fragments can cause more damage as they shower down on the public and infrastructure below. An example of this is in the 1995 Oklahoma City bombing: 198 people suffered direct glass related injuries such as lacerations or abrasions from flying glass debris, a further 265 people suffered hearing impairment from the blast where glass windows were shattered and no longer able to exhibit their acoustic insulation properties [7]. Glazing and structural technologies to prevent these phenomena will be highlighted in this paper.

2. Case Study: Spatial Roof of the Erasmusline, Hague, The Netherlands

A long span spatial roof of the Erasmusline railway station in Hague, The Netherlands has been chosen for this study, as shown in Figure 2. The structure optimises a gridshell roof canopy with singly curved glass along platform level and double curved at the "closed end". It is 90m long and spans 17m across the platform, the maximum height above platform level is 6m and is formed of rectangular hollow sections for the mesh and cold formed laminated glass as the canopy [8]. The boundary conditions use one pinned connection on either side of the roof connecting to the edge beam to allow for the required rotation, the remaining connections are able to slide longitudinally, to allow for thermal effects. The laminate construction of the roof canopy uses 10mm plies according to Helbig et al. [8] and a (assumed) 5mm interlayer. The 15kg blast will be located in the "closed" end of the structure where the danger to both life and structure will be most catastrophic.

This study aims to model both the non-linear response of the laminated glass shell panel as well as the breakage configuration of the entire structure due to blast. The former involves a single panel that is modelled similar to the research conducted by Kranzer et al. [9] and Hooper et al. [10] and the latter reflects the work of Kaewunruen et al. [2], where the entire Canary Wharf underground station canopy was modelled against blast effects. It is a common approach to model laminated glass as monolithic when analysing against short term loads. This is because the interlayer behaves as a relatively stiff material in short term loads like blast. The shear modulus of 10MPa results in bending stresses similar

to that of a monolithic pane under blast loads, where these similarities end is when the glass breaks. The transition of strength between the layers of the laminate throughout the stages of blast loading was an important phenomenon to attempt capture by the model. The structure has been exposed to a uniformly distributed and an exponentially decaying blast load. This can be calculated from the LS-DYNA pre-post using the empirical function `LOAD_BLAST_ENHANCED`. It is a continuum solver and models a spherical TNT charge in free air with normal temperature and pressure acting on a Lagrangian structure. FE model of the structure has been validated by experiments [8].

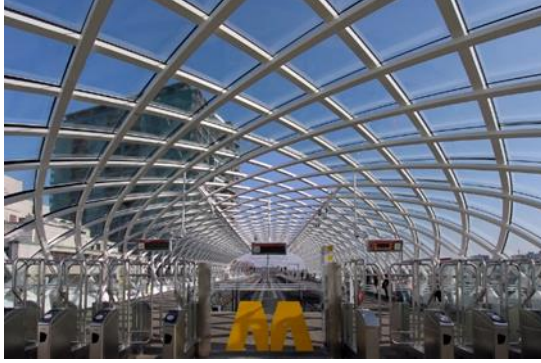


Figure 2: The Erasmusline, The Hague, Netherlands

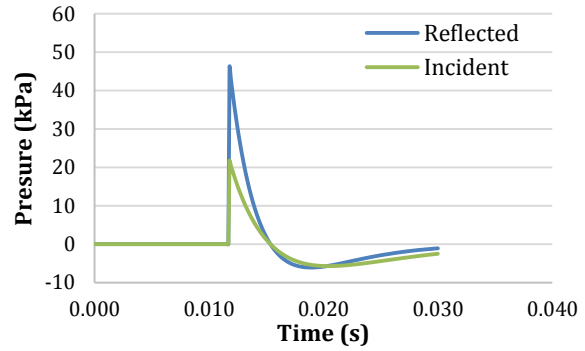


Figure 3: Validation of blast pressure

Table 1: Comparison of blast pressure

	FEM (This study)	Kranzer et al. [9]	UFC [9]
Incident pressure	19.67kPa	N/A	25.00kPa
Reflected pressure	46.07kPa	65.00kPa	50.00kPa

3. Results and discussion

Figure 3 shows the reflected and incident blast pressures that are experienced by the plate adopted by Kranzer et al. [9]. Table 1 shows the data collected from Kranzer et al [9], UFC [9] and the finite element model, to compare the magnitudes of the incident and reflected blast pressures. The table shows that the CONWEP method used by the `LOAD_BLAST_ENHANCED` function in LS-DYNA mimics the Friedlander equation used in UFC [9] effectively.

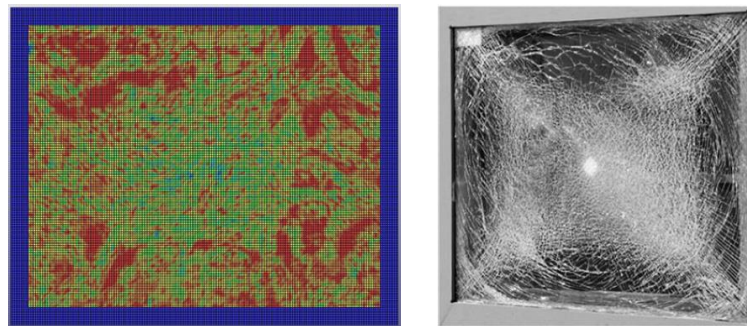


Figure 4: Blast damage on glass structure (left: this study; right: experiment by [9]).

This study has been used to illustrate the adequacy of the boundary conditions through the distribution of cracks compared to the experiment. The finite element model and experiment crack pattern can be found in Figure 4. This model used `MAT_032`, due to its failure algorithm mentioned in table 2, which shows good agreement to the experimental results. A potential reason for the lack of cracking in the centre of the finite element model could be attributed to the size of the cracks that formed in the specimen. The lack of cracking in the centre of the finite element model could potentially be attributed to excessive deflections of the larger cracks around the outside which relieve the stress on the inner elements. This hasn't occurred in Kranzer et al.'s [9] specimen as micro-cracks are still able to withstand some stresses to transfer to the centre elements.

4. Conclusion

This research investigated the blast effects on highly non-linear, thin shell structures, through a rigorous parametric study to identify the suitable material nonlinearities, as well as an effective model of a light rail station in The Netherlands to model the geometric nonlinearities of its roof canopy. The study has critically reviewed and established a suitable model for the nonlinearities of laminated glass shell structures. Experimental data have been used to validate the finite element models in LS-DYNA. The study reveals that the shell model subsequently reacted stiffer than the experiment when modelling the post-crack phase. The crack propagation of glass shell structure can be simulated precisely. It is also found that erosion criteria assigned to each layer have proven to lead to premature deletion from the model and hence greater deflections.

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